LA-UR-83-3096

CONF-8309163--2

LA-UR--83-3096

DE84 001748

TITLE: NO-NEUTRINO DOUBLE BETA DECAY: MORE THAN ONE NEUTRINO?

AUTHOR(S): S(imon) P(eter) Rosen, T-DO

SUBMITTED TO: AIP Conference Proceedings, Virginia Polytechnic and State Univ., Blacksburgh, VA, September 12-14, 1983

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

NO-NEUTRINO DOUBLE BETA DECAY: MORE THAN ONE NEUTRINO?

S. P. Rosen

T-Division, Los Alamos National Laboratory,
Los Alamos, New Mexico 87545

ABSTRACT

Interference effects between light and heavy Majorana neutrinos in the amplitude for no-neutrino double beta decay are discussed. The effects include an upper bound on the heavy neutrino mass, and an A dependence for the effective mass extracted from double beta decay. Thus the search for the no-neutrino decay mode should be pursued in several nuclei, and particularly in Ca^{48}, where the effective mass may be quite large.

MORE THAN ONE VIRTUAL NEUTRINO?

The problem I wish to address in this talk is how to reconcile the lower bound on the neutrino mass[1],

$$m_\nu > 20 \text{ ev} \tag{1}$$

recently obtained by the ITEP group from tritium beta decay with the much smaller upper bound[2],

$$m_\nu < 6 \text{ ev} \tag{2}$$

obtained by the Heidelberg group from a comparison of double beta decay lifetimes for the isotopes ^{128}Te and ^{130}Te of Tellurium. Let me say at the outset that I recognize the serious reservations held about the tritium experiment[3] and the need to await confirmation by another experiment; but I would ask you to indulge me in a "theorist's license" to imagine that there is a germ of truth in what the ITEP group is telling us. I should also point out that there have been other indications of a conflict between tritium beta decay and double beta decay in the theoretical calculations of Haxton, Stephenson, and Strottman[4]; from the experimental data on Se^{82} and Ge^{76}, these authors find that m_ν cannot have a value much larger than 10-20 ev. The work I shall discuss is based on a recent paper by A. Halprin, S. Petrov and myself[5].

One simple solution to the problem is to conclude that the electron-neutrino is a Dirac particle: the no-neutrino double beta decay transition (see Fig. (i)) is then forbidden, and the observed lifetimes cannot be used to extract a bound on the neutrino mass. Given the gauge theoretic pre-disposition towards Majorana neutrinos, however, this solution is not particularly satisfactory. We therefore turn to another alternative, first observed by Doi, Kotani, Takasugi and Nishiura[6] and subsequently taken up by Wolfenstein[7], namely that if more than one neutrino mass-eigenstate should contribute to the no-neutrino amplitude, there may be cancellations amongst these contributions. Thus in double beta decay one may be measuring differences between masses, whereas in tritium beta decay one measures an average mass. Obviously there is likely to be li[illegible]e overlap between the difference and the average.

To understand how this cancellation may arise, let us consider the amplitude for the diagram in Fig. (i) when the charged weak leptonic current has the form:

$$L_\lambda = (\bar{e}\gamma_\lambda(1+\gamma_5)[C\psi_\nu + D\psi_\nu c]) \quad . \tag{3}$$

The appearance of both the Dirac neutrino field, ψ_ν, and its charge conjugate, $\psi_\nu c$, is necessary if the neutrino emitted by the first neutron, n_1, in the nucleus is to be re-absorbed by the second neutron, n_2. The helicity factor $(1+\gamma_5)$ in L_λ implies that the neutrino emitted by n_1 is right-handed, while the neutrino absorbed by n_2 is left-handed! Thus the neutrino must flip its helicity as it travels from n_1 to n_2. Since no right-handed current is present in L_λ, the helicity flip will occur only if the neutrino has a non-zero rest-mass. The amplitude for Fig. (i) is therefore of the form:

$$A_{\beta\beta} = m_\nu \; CD \; F(\nu) \tag{4}$$

where $F(\nu)$ is a factor describing the propagation of the neutrino through the nucleus and the appropriate nuclear matrix element.

Now there are two simple choices for the coefficients C and D which are analogous to the original CP eigenstates K_1 and K_2 in the neutral kaon system. They are:

$$C=+D = 1/\sqrt{2}; \; \phi_\nu=1/\sqrt{2}(\psi_\nu+\psi_\nu c); \; CP=+1 \qquad (K_1) \tag{5a}$$

$$C=-D = 1/\sqrt{2}; \; \chi_\nu=1/\sqrt{2}(\psi_\nu-\psi_\nu c); \; CP=-1 \qquad (K_2) \tag{5b}$$

Should it happen that both neutrinos, ϕ_ν and χ_ν, contribute to no-neutrino double beta decay, then because of their opposite CP eigenvalues, they will contribute to the overall amplitude with opposite signs:

$$A_{\beta\beta}(\phi) + A_{\beta\beta}(\chi) = \frac{1}{2}[m_\phi F(\phi) - m_\chi \; F(\chi)] \tag{6}$$

In other words, Majorana neutrinos of opposite CP tend to cancel one another in double beta decay[7,8].

Before examining the structure of this cancellation, we must study the neutrino propagator as a function of neutrino mass. In momentum space, the propagation can be written as

$$P_\nu = \frac{m_\nu \langle p\rangle}{m_\nu^2+\langle p\rangle^2} \tag{7}$$

where $\langle p\rangle$ is the average neutrino momentum. The average separation $\langle r_{12}\rangle$ between nucleons inside the nucleus provides an effective cut-off on the amplitude, which takes the form:

$$\langle p\rangle \cong \frac{1}{\langle r_{12}\rangle} \cong \frac{1}{R} \cong 30\text{-}50 \text{ Mev} \tag{8}$$

Two extreme cases of the propagator occur when the neutrino mass is either very much smaller than $\langle p\rangle$, or very much larger. When $m_\nu \ll \langle p\rangle$ (the low mass case), the propagator is

$$P_\nu \cong \frac{m_\nu}{\langle p\rangle} \quad \text{(low mass case)} \tag{9}$$

and when $m_\nu \gg \langle p\rangle$, the propagator becomes

$$P_\nu \cong \frac{\langle p\rangle}{m_\nu} \quad \text{(high mass case)} \quad . \tag{10}$$

In configuration space, the low mass case corresponds to a Coulomb-like factor $m_\nu \langle 1/r_{12}\rangle$ evaluated with respect to the two-nucleon correlation function, and the high mass case to a Yukawa-like factor[9],

$$P_\nu(r_{ij}) = m_\nu \langle \frac{e^{-m_\nu r_{ij}}}{r_{ij}} \rangle \quad . \tag{11}$$

The general shape of $P_\nu(r)$ is shown in Fig. (ii). As a general rule, the low mass case applies to light neutrinos with masses in the 10ev range, while the high mass case is relevant for neutrinos with masses of a few hundred Mev or more.

We now turn to the extraction of masses from the ITEP and double beta decay experiment: when the neutrino coupled to the electron in the charged weak current is assumed to be:

$$\nu_e = (\cos\theta)\,\phi + (\sin\theta)\chi \tag{12}$$

where ϕ and χ are mass eigenstates with CP = +1 and -1 respectively. The mass measured in tritium beta decay is then a weighted sum of m_ϕ and m_χ:

$$m^2(\bar{\nu}_e) = |m_\phi^2\cos^2\theta + m_\chi^2\sin^2\theta| \quad . \tag{13}$$

In view of oscillation experiments[10], we take the mixing angle to be small,

$$\sin^2\theta \leq 0.1 \tag{14}$$

and set

$$m(\bar{\nu}_e) \cong m_\phi \tag{15}$$

from the 1980 results of ITEP[11], we have

$$14 \lesssim m_\phi \lesssim 45 \text{ ev} \tag{16a}$$

and from the 1983 results[1], we find

$$20 \text{ ev} \lesssim m_\phi \quad . \tag{16b}$$

With the above assumptions for ν_e, the "mass" measured in no-neutrino double beta decay has the general form:

$$m_{\beta\beta}(\nu_e) = |m_\phi \cos^2\theta - F\,(m_\chi,A)\, m_\chi \sin^2\theta| \tag{17}$$

where the negative sign comes from the odd relative CP of the Majorana neutrinos ϕ and χ, and the function $F(m_\chi,A)$ is essentially the ratio of their configuration space propagators:

$$F(m_\chi,A) = \left(\left\langle \frac{e^{-m_\chi r_{12}}}{r_{12}} \right\rangle \Big/ \left\langle \frac{1}{r_{12}} \right\rangle\right) \quad . \tag{18}$$

When m_χ is of order a few times 10 ev (low mass case), then F is unity <u>for all values of A</u>:

$$F(m_\chi,A) = 1 \text{ for all A, } m_\chi \cong 0(10\text{ev}). \tag{19}$$

and the value of $m_{\beta\beta}(\nu_e)$ will be the same for all double beta decaying parent nuclei. This is the case previously considered by Doi et al[8], and by Wolfenstein[7].

Here we consider the case in which m_χ is of order several hundred Mev or more (the high-mass case). Neutrino oscillations are then forbidden for low-energy neutrinos, but universality sets a limit on the mixing angle,

$$\sin^2\theta \lesssim 0.05 \tag{20}$$

because the heavy neutrino χ cannot be emitted in nuclear β-decay. Double beta decay experiments will yield two qualitative results for the various masses:

(1) There must be an <u>upper bound</u> on m_χ: if m_χ becomes too large, it cannot cancel enough of m_ϕ to bring $m_{\beta\beta}(\nu_e)$ down from the ITEP range (eq. 1) to the range of the Tellurium ratio experiment (eq. 2). This situation is illustrated in Fig.

(iii). (2) The effective mass $m_{\beta\beta}(\nu_e)$ must vary from nucleus to nucleus; in general $m_{\beta\beta}$ will <u>increase</u> as A <u>decreases</u>, but the detailed behaviour will depend on the nucleon-nucleon correlation function.

To illustrate these features we consider two examples with specific correlation functions. The first one is a uniform correlation with an infinitely hard core at radius $r_c \cong 0.5F$ and a cut-off at the nuclear diameter[9]:

$$P(r_{12}) = [\tfrac{4\pi}{3}(8R^3 - r_c^3)]^{-1}\ \theta(r_{12}-r_c)\theta(2R-r_{12}) \tag{21}$$

where R is the nuclear radius

$$R = 1.2A^{1/3}\ F \quad . \tag{22}$$

The ratio of propagators is given by

$$F(m_\chi,A) = 0.5\ (m_\chi R)^{-2}[(1+m_\chi r_c)e^{-m_\chi r_c}-(1+2m_\chi R)e^{-2m_\chi R}] \tag{23}$$

and it is proportional to $A^{-2/3}$. From the universality constraint (eq. (20)), and the ITEP and Tellurium ratio results (eqs. (1) and (2)), we find that

$$M_\chi < 3.5\ \text{Gev} \quad . \tag{24}$$

If we choose $\sin^2\theta$ and m_χ, so that $m_{\beta\beta}(\nu_e)$ vanishes for Tellurium, we then find that because $F(m_\chi,A)$ varies as $A^{-2/3}$, the bounds on $m_{\beta\beta}(\nu_e)$ for lighter nuclei are quite different:

$$\begin{aligned} &5\text{ev} < m_{\beta\beta}(\nu_e)\Big|_{Se^{82}} < 16\text{ev} \\ &13\text{ev} < m_{\beta\beta}(\nu_e)\Big|_{Ca^{48}} < 43\text{ev} \\ &\qquad\qquad \text{when } m_{\beta\beta}(\nu_e)\Big|_{T_e} \cong 0 \quad . \end{aligned} \tag{25}$$

If we follow Doi et al[12] and take

$$\rho \sim \delta\ (r_{12}-R) \tag{26}$$

then we find that:

$$F_2(m_\chi,A) \quad 1.67\ e^{-m_\chi R} \tag{27}$$

and hence that

$$m_\chi \lesssim 500 \text{ Mev} \tag{28}$$

Again, if we choose m_ϕ, m_χ, and $\sin^2\theta$ so that $m_{\beta\beta}$ vanishes for Tellurium, namely

$$m_\phi=15\text{ev},\ m_\chi=150 \text{ Mev},\ \sin^2\theta = 6.3\times10^{-6} \tag{29}$$

then we find the following effective masses for lighter nuclei:

Isotope	$m_{\beta\beta}$(ev)
Te^{130}	0
Se^{82}	18
Ge^{76}	21
Ca^{48}	45

(30)

In both of these examples, the lightest nucleus, namely Ca^{48}, has the largest effective mass. Thus it is well worthwhile to revive efforts to look for double beta decay in this nucleus[13].

The lesson of these examples is that one must look for no-neutrino double beta decay in a range of nuclei and determine whether the effective mass does or does not depend upon A. If it is found to have an A dependence, then we can conclude that heavy Majorana neutrinos must play a role in no-neutrino double beta decay. If the effective mass is independent of A, then we learn that only light neutrinos are important for the process.

As a final note, we point out that were ϕ left-handed and χ right-handed, there would be very little interference between the appropriate exchange diagrams because the final state electrons would have opposite helicities. Thus it is essential for the interference that the virtual neutrinos be coupled with the same helicity.

References

1. V. Lubimov, Report to European Physical Society Conference, Brighton, England, July 1983.
2. T. Kirsten, H. Richter, and E. Jessburger, Phys. Rev. Lett. 50, 474 (1983).
3. See talk by J. Simpson, these proceedings.
4. W. Haxton, G. J. Stephenson, Jr. and D. Strottman, Phys. Lett. 125B, 335 (1983).
6. M. Doi et al Phys. Lett 102B, 323 (1981).
7. L. Wolfenstein, Phys. Lett. 107B, 77 (1981).
8. B. Kayser and A. Goldhaber, to be published.
9. A. Halprin, P. Minkowski, H. Primakoff, and S. P. Rosen, Phys. Rev. D13, 2567 (1976).
10. See talk by F. Boehm, these proceedings.

11. V. Lubimov et al, Phys. Lett. 94B, 266 (1980).
12. M. Doi et al, Prog. Theoret. Phys. 66, 1735 (1981).
13. R. Bardin, P. Gollon, J. Ullman, and C. S. Wu, Nucl. Phys. A158, 337 (1970).

No – Neutrino $\beta\beta$ Decay

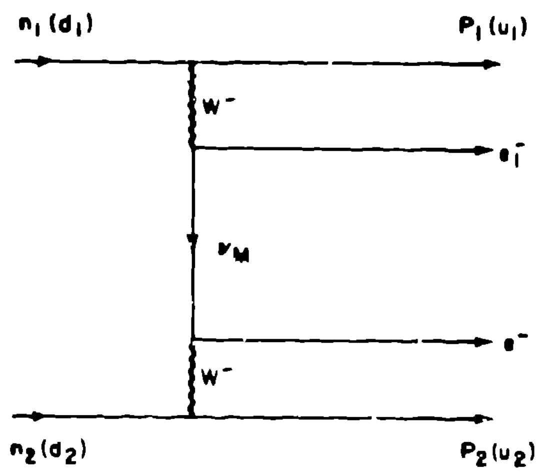

Figure (i) : Neutrino exchange diagram for no-neutrino double beta decay.

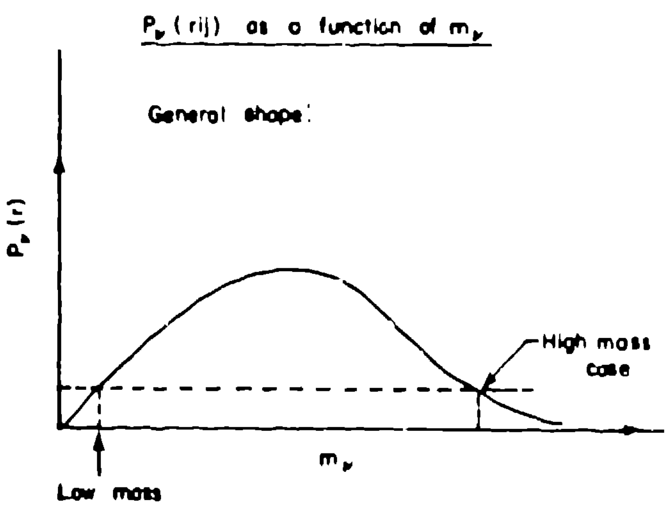

Figure (ii) :General form of neutrino propagation as a function of neutrino mass.

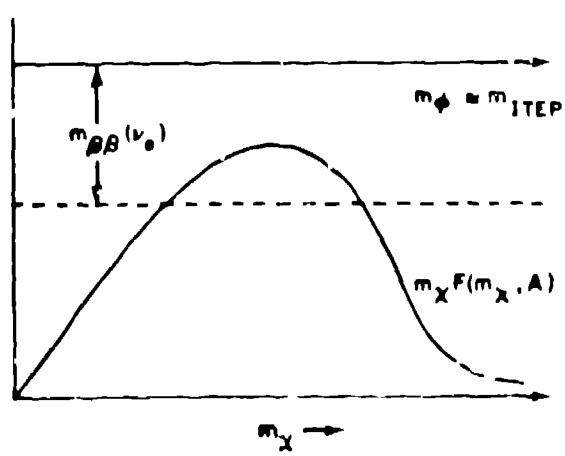

Figure (iii):Bounds on m_χ imposed by tritium beta decay and Tellurium ratio experiments.